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Preferential Flow Estimates to an Agricultural Tile Drain with Implications for Glyphosate Transport

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ABSTRACT

Agricultural subsurface drains, commonly referred to as tile drains, are potentially significant pathways for the movement of fertilizers and pesticides to streams and ditches in much of the Midwest. Preferential flow in the unsaturated zone provides a route for water and solutes to bypass the soil matrix and reach tile drains faster than predicted by traditional displacement theory. This paper uses chloride concentrations to estimate preferential flow contributions to a tile drain during two storms in May 2004. Chloride, a conservative anion, was selected as the tracer because of differences in chloride concentrations between the two sources of water to the tile drain, preferential and matrix flow. A strong correlation between specific conductance and chloride concentration provided a mechanism to estimate chloride concentrations in the tile drain throughout the storm hydrographs. A simple mixing analysis was used to identify the preferential flow component of the storm hydrograph. During two storms, preferential flow contributed 11 and 51% of total storm tile drain flow; the peak contributions, 40 and 81%, coincided with the peak tile drain flow. Positive relations between glyphosate [N-(phosphonomethyl)glycine] concentrations and preferential flow for the two storms suggest that preferential flow is an important transport pathway to the tile drain.

Agricultural subsurface drains, commonly referred to as tile drains, are transport pathways for the movement of fertilizers and pesticides to streams and ditches in much of the Midwest. Tile drains are used in areas with poorly drained soils; they facilitate access to and cultivation of agricultural land. During the 1980s, the USDA estimated that approximately 50% of all cropland in Indiana was drained; of that cropland, approximately 70% was drained by tile drains (USDA, 1987). The USDA estimated that Indiana ranked second in the U.S.A. in total land area drained by surface and subsurface drainage (USDA, 1987). In agricultural watersheds, tile drains are a primary N transport pathway to streams (Soenksen, 1996; Fenelon and Moore, 1998; David et al., 1997). David et al. (1997) estimated that in their east-central Illinois study area, 49% of the inorganic N pool in agricultural soils was leached to tile drains and exported to streams. Agricultural fields lose N whenever tile drains flow, and the majority of N transport through tile drains corresponds to the flow of the majority of water through the tile drains (Brouder et al., 2005; Kladivko et al., 2004; Gentry et al., 1998; David et al., 1997).

In agricultural watershed studies, tile drains also were found to be pesticide transport pathways to streams (Soenksen, 1996; Fenelon and Moore, 1998). In addition, pesticides with soil-adsorbing properties have been found in tile drain effluent shortly after application (Kladivko et al., 1991). The significance of tile drains to pesticide transport is related to the environmental setting. Kladivko et al. (2001) in a review of tile drain pesticide transport studies found that surface runoff usually moves a greater mass of pesticides to streams than do tile drains. In areas where surface runoff is minimal, however, tile drains may be of greater significance for transport of pesticides to streams than surface runoff. In agricultural settings, the movement of water from the field surface to tile drains is an important component in understanding solute transport.

Traditionally, water movement through soils has been considered as soil matrix flow or displacement. Such flow or displacement, however, cannot account for the rapid appearance in tile-drain effluent of pesticides after application (Kladivko et al., 1991). The rapid movement of water and solutes through the unsaturated or vadose zone can be explained by preferential flow pathways such as macropores, shrink–swell cracks, wormholes, and root casts (Kladivko et al., 1991; White, 1985; Thomas and Phillips, 1979). Kladivko et al. (2001) suggest that pesticide transport to tile drains soon after application is primarily by preferential flow. Kung et al. (2000) and Gentry et al. (2000) also note that preferential flow transports N to tile drains when newly applied. However, in situations where N is diffusely distributed through the soils, preferential flow may contribute water with low N concentrations to tile drains (Kladivko et al., 2004). Preferential flow in the unsaturated zone provides a route for water to bypass the soil matrix; in contrast, soil matrix flow allows more time than preferential flow for soil-adsorbing pesticides to adhere to soil particles. Thomas and Phillips (1979) describe water movement through the unsaturated zone in three ways. Displacement refers to the piston-like flow of water through the soil matrix, which is the conventional model of water moving through the unsaturated zone; flow through macropores (preferential flow) indicates nondisplacement of soil matrix water; partial displacement is a combination of displacement and preferential flow and is usually how water moves through soils. In this paper, the term preferential flow will be used to indicate water bypassing the soil matrix; the term matrix flow will be used to describe water moving through soils by displacement.

Macropores may occupy only a small fraction of the total soil volume; however, they can have a significant effect on the rate of water movement through the soils (White, 1985). Instruments to map preferential flow paths do not exist and conventional techniques to measure hydraulic properties of soils cannot quantify preferential flow paths (Kung et al., 2000). Tile drain monitoring, how-

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ever, can provide an effective field-scale mechanism for quantifying the effects of preferential flow on pesticide and nutrient transport. Tile drains integrate spatial variability of preferential and matrix flow on a field scale and are usually present in silty, clayey soils that exhibit preferential flow (Richard and Steenhuis, 1988).

The need to understand preferential flow in the transport of pesticides and nutrients to tile drains has led to numerous studies that used various techniques to quantify preferential flow. Dye- and chemical-tracer studies that use breakthrough curves have quantified preferential flow transport under various field conditions (Gish et al., 2004; Kung et al., 2000; Richard and Steenhuis, 1988). In addition, simple to more complex digital or numerical transport models have been developed to estimate preferential flow transport of solutes (Steenhuis et al., 1994, 1997; Kung et al., 2000). Kumar et al. (1997) used a dual-porosity model (preferential and matrix flows) combined with surface water hydrograph-separation techniques to estimate the contribution of preferential flow to tile drains in Iowa. Most of the preferential flow studies, with the exception of Kumar et al. (1997), use an applied tracer or the appearance of a pesticide in tile drain effluent as an indicator of preferential flow. The findings from these applied tracer and pesticide studies have proven to be invaluable in understanding preferential flow.

OBJECTIVES

This paper builds on previous research by evaluating preferential flow without the use of applied tracers or breakthrough curves. Specifically, the primary objective of this paper is to use tile drain flow, major ion chemistry, and specific conductance data collected from a tile drain to evaluate preferential flow contributions to the tile drain effluent during two storms in May 2004. A conservative, two-source mixing analysis using chloride and water mass balance was used to produce a tile drain flow hydrograph that is separated into preferential and matrix flow contributions. Conservative chemical mixing analysis or end-member mixing analysis, based on conservation of mass equations, has been used in varying degrees of complexity for hydrograph separation of small streams. Hyer et al. (2001) and Burns et al. (2001) are examples of conservative chemical mixing analysis in hydrograph separation of small streams.

In addition, the separated hydrographs were compared to tile drain effluent concentrations of glyphosate [N-(phosphonomethyl)glycine], a herbicide that strongly sorbs to soil, with the objective of examining how preferential flow may affect pesticide transport. Finally, a November 2004 storm is compared to the two May 2004 storms to examine how antecedent conditions may affect contributions of water to the tile drain from preferential and matrix flow.

MATERIALS AND METHODS

Site Description

The tile drain used in this analysis is in the Leary Weber Ditch Watershed, 32 km east of Indianapolis in rural Hancock County, Indiana. The tile drain is on an active, private farm that uses a corn and soybean crop rotation. This tile drains the field immediately to the south of the ditch (Fig. 1) and was selected because of its medium level of flow duration compared to the other tile outlets draining to the ditch. It is a single tile drain, not a network of tile drains. Its drainage area is in a single field of one crop type and does not have surface tile inlets or other man-made connections to the surface. The majority of the tile drains installed in this watershed are 30 or more years old, as was the one used in this study. There were at least 15 other tile drain outlets along the 0.4-km stretch of ditch near the study tile drain outlet. The exact extent of the study tile drain and other tile drains in the watershed is unknown. It was estimated that this tile drain runs approximately 1 to 1.5 m underground, sloping toward the ditch. The smooth-walled polyvinyl chloride tile drain outlet is 20.3 cm in diameter, approximately 2 m below the field surface.

The soils of the Leary Weber Ditch Watershed are in the Crosby-Brookston soil association (fine, mixed, active, mesic Aeric Epiaqualfs and fine-loamy, mixed, superactive, mesic Typic Argiaquolls). Soils in this association are characterized as poorly drained, nearly level silt loams and silty clay loams formed in glacial till or in loamy sediment and the underlying glacial till (USDA, 1978). These high clay and organic-matter soils may have a higher tendency for the formation of preferential flow paths than more coarse-textured and poorly structured soils (Kladivko et al., 1999; Richard and Steenhuis, 1988).

Data Collection

An autosampler collected water samples from the tile drain effluent during periods of increased tile drain flow related to storms. The autosampler was triggered by a datalogger connected to a pressure transducer that measured water depth in the tile drain. A predetermined rise in water level inside the tile drain initiated the autosampler to collect samples on an hourly basis through the rise and peak of the storm hydro-

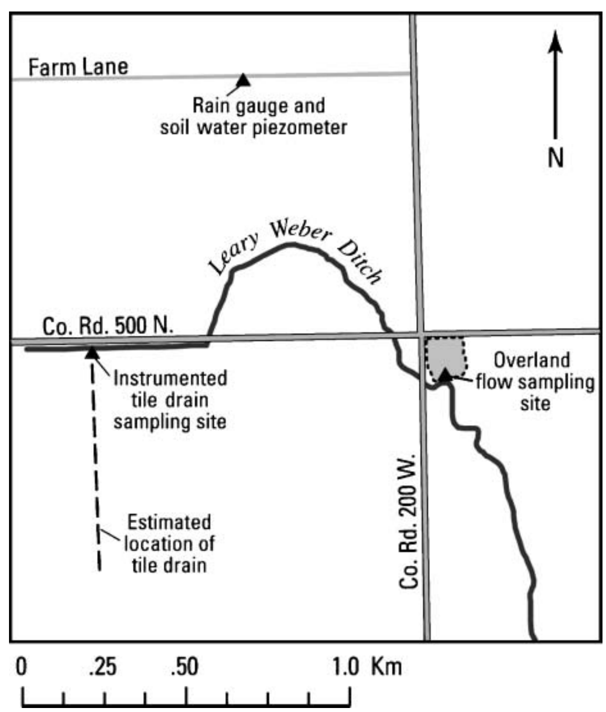

Fig. 1. Leary Weber Ditch study site in Hancock County, Indiana.

graph. During the recession of the hydrograph, the sampling interval was lengthened to every 2 or 4 h. Five samples from each of the two storms in May 2004 and one November 2004 storm were selected for chemical analysis, based on their relation to the rise, peak, and recession of the hydrograph. Additionally, between storms and during periods of low flow, grab samples were collected manually from the tile-drain effluent.

An autosampler collected samples of surface water runoff from an overland flow site that intercepted the runoff before entering the ditch. These samples were used to estimate chloride concentrations of water on the soil surface. The tile drain and the overland flow fields were treated similarly in terms of potash application. The overland flow site is approximately 1.2 km east of the tile drain outlet (Fig. 1). Field runoff samples were collected throughout the storm hydrograph from a flume installed at the edge of the field. Both storms in May 2004 had measurable field runoff. The November 2004 storm did not have measurable field runoff, therefore, no runoff samples were collected. Cultivation and fertilization practices, and potassium chloride applications on the overland flow and tile drain sites were the same during the study period.

Water sample handling, filtering, and preparation followed, according to the USGS National Field Manual for the Collection of Water Quality Data (USGS, 2006). Samples were iced and shipped overnight for analysis at the USGS National Water Quality Laboratory (NWQL) in Denver, CO, and the Organic Geochemistry Research Laboratory (OGRL) in Lawrence, KS. The NWQL analyzed the water samples for major inorganics following the methods described by Fishman (1993), Fishman and Friedman (1989), and the American Public Health Association (1998). OGRL analyzed the water samples for glyphosate, following the methods described in Lee et al. (2002).

Tile drain flow was estimated from stage discharge relations and data from a modified circular flume (Richard Cooke, personal communication, 2004; Samani and Herrera, 1996; Samani et al., 1991; Samani and Magallanez, 2000; Hager, 1988). Numerous stage and discharge measurements under varying flow conditions were made on-site at the tile drain outlet to calibrate the flume. Partial and full submergence greater than 80% of the flume outlet, however, complicated the accuracy and reliability of the flume calibration. Therefore, on-site direct measurements of tile drain flow under partial and full tile outlet submergence were used in conjunction with the circular flume estimates to obtain a continuous record of flow. Tile drain-flow data were collected in 15-min intervals from 2 Apr. 2004 through 3 Dec. 2004.

A specific conductance and temperature probe connected to a datalogger was placed in the tile drain approximately 3 m from the outlet. This probe recorded data in 15-min intervals from 2 Apr. 2004 through 3 Dec. 2004. To monitor instrument drift and biofouling, calibration of the specific conductance probe was checked regularly against standard solutions.

Rainfall amounts and water table levels were recorded at another field approximately 0.8 km to the northeast of the tile drain site (Fig. 1). Hourly rainfall data were collected with a tipping-bucket rain gauge and a datalogger. Water table levels were recorded in a piezometer constructed of 10.2-cm diameter polyvinyl chloride with a 0.61-m screen placed 2 m below land surface. The piezometer was installed in December 2002, following procedures outlined in Lapham et al. (1996). Equipment installation activities located a tile drain within 20 m of the piezometer; however, this tile drain was not monitored as part of the study. The piezometer was equipped with a pressure transducer that recorded continuous data in 15-min intervals from November 2003 through December 2004.

Conservative Mixing Analysis

Flow, major ion chemistry, and specific conductance data collected during storm and baseflow conditions provided the components necessary to evaluate preferential flow in the tile drain hydrograph. A key requirement in this effort was that the major ion chemistry of preferential flow water was different than that of matrix flow water. Steenhuis et al. (1994) describe that preferential flow water reflects the chemistry of water from the soil surface, whereas matrix flow reflects the chemistry of water that has had more contact time with soils. This analysis combines soil matrix water and shallow ground water (hereafter referred to as matrix water).

The mixing analysis for chloride used two sources: water from the soil surface (preferential flow) and matrix water. Chloride concentrations in the overland flow water samples collected in May 2004 were assumed to represent the preferential flow water. The average chloride concentration in the 12 overland flow samples was 0.91 mg L^{-1}, with a range between 0.34 and 1.54 mg L^{-1}. Chloride levels in the tile drain baseflow samples collected between storms were assumed to represent matrix water. The average chloride concentration in the four baseflow samples was 10.96 mg L^{-1}, with a range between 8.74 and 12.03 mg L^{-1}. This analysis assumes that all the water flowing from the tile drain during baseflow conditions was matrix water. Another assumption in this analysis is that the concentrations from these two sources were constant during these storms. In reality, this assumption is too rigid to be completely accurate, but it is probably reasonable for the short durations of each storm. The levels of chloride in the two sources likely vary over periods of time longer than used in this analysis. For example, chemical application may affect chloride concentrations in the preferential flow water, or excessive wet periods may affect the concentration in the matrix water. The last application of muriate of potash (potassium chloride) before the May 2004 storms was during fall 2002. The fields at the tile drain and the overland flow sites were treated equally in muriate of potash application and it is assumed that the surface chloride levels at these two sites were similar during the May 2004 storms. This assumption adds uncertainty to the analysis because it is not likely that the surface chloride levels between these two sites were exactly equal. The application of muriate of potash during fall 2004 also directly affects this assumption for the November 2004 storm and is discussed later. Another factor that may affect this assumption is that preferential flow contributes water to the shallow ground water. The short duration of the May 2004 storms, the intensity of storms, and the use of actual tile drain low flow and overland flow chloride chemistry data may minimize the adverse impacts on the mixing models that result from adopting these assumptions.

The May 2004 tile drain flow, major ion chemistry, and specific conductance data also supports the requirement that the major ion chemistry of water moving through preferential flow was different than that for matrix flow. Table 1 shows the Spearman ρ correlation coefficients (a non-parametric test for the strength of a relation between variables) for tile drain flow and specific conductance in relation to the major ions. For the May 2004 storms, there was a strong positive correlation between specific conductance and chloride ($\rho = 0.99$, $p < 0.01$) and a strong negative correlation between specific conductance and tile drain flow ($\rho = -0.87$, $p < 0.01$) and chloride and tile drain flow ($\rho = -0.88$, $p < 0.01$). These correlations suggest that lower ionic-strength water from the field surface contributed to the tile drain flow at an increasing rate as the tile drain flow increased. There are no surface inlets to this tile drain; therefore, this lower ionic-strength water likely reached the tile drain by preferential flow.

Table 1. Spearman ρ correlation for major ions, specific conductance, and tile drain flow for the May and November 2004 storms at the Leary Weber Ditch tile drain study site†.

	May 2004 storms						November 2004 storm					
	Specific conductance		Tile drain flow		Range of parameter value		Specific conductance		Tile drain flow		Range of parameter value	
Parameter	**ρ**	***p*-value**	**ρ**	***p*-value**	**min**	**max**	**ρ**	***p*-value**	**ρ**	***p*-value**	**min**	**max**
Specific conductance (μSm cm^{-1})	–	–	−0.87	0.0059	188	511	–	–	−0.16	0.6225	506	525
Tile flow (L s^{-1})	−0.87	0.0059	–	–	0.25	11.64	−0.16	0.6225	–	–	0.37	4.05
Calcium (mg L^{-1})	0.94	0.0032	−0.81	0.0103	26.4	71.4	0.35	0.2985	−0.56	0.0874	56.3	70.6
Chloride (mg L^{-1})	0.99	0.0018	−0.88	0.0050	2.82	11.29	−0.27	0.4119	0.92	0.0064	27.0	42.34
Fluoride (mg L^{-1})	−0.66	0.0346	−0.63	0.0468	0.17	0.27	0.10	0.7704	−0.05	0.8557	0.18	0.38
Magnesium (mg L^{-1})	0.95	0.0029	−0.83	0.0084	7.36	23	0.28	0.4118	−0.58	0.0809	18.1	21.81
Potassium (mg L^{-1})	−0.85	0.0072	0.61	0.0572	0.22	1.03	0.15	0.6616	0.39	0.2446	0.34	0.80
Silica (mg L^{-1})	0.58	0.0679	−0.39	0.2154	5.52	8.87	0.32	0.3429	−0.53	0.1096	7.07	8.58
Sodium (mg L^{-1})	0.87	0.0060	−0.69	0.0285	0.78	1.89	0.24	0.4769	−0.62	0.0586	1.63	2.07
Nitrate (mg L^{-1})	0.55	0.0872	−0.22	0.4713	3.27	9.24	−0.09	0.7845	0.00	1.0000	8.51	10.22
Sulfate (mg L^{-1})	0.85	0.0074	−0.70	0.0252	4.93	10.4	0.30	0.3813	−0.81	0.0148	9.36	10.80

† All concentrations are mg L^{-1}; specific conductance units are μSm cm^{-1}; and tile drain flow units are L s^{-1}.

Given these strong correlations and the fact that chloride is a chemically conservative anion, chloride was chosen as the tracer for the May 2004 storms. A relation between specific conductance and chloride concentration was developed through regression analysis to estimate the chloride concentrations in the tile drain effluent throughout the May 2004 storm hydrographs (Fig. 2).

The relations observed between tile drain flow and the major ion chemistry of the tile drain effluent during the May 2004 storms was not apparent during a November 2004 storm (Table 1). The simple mixing analysis and subsequent hydrograph separation were not performed for the November 2004 storm; however, the major ion chemistry and the other data from this storm are used later in the discussion of the findings.

The tile drain flow, estimated tile drain effluent chloride concentrations, and the assumed chloride concentrations in preferential flow and matrix flow were used with the following conservation of mass equations to estimate the contributions from both sources:

$$Q_{td} = Q_m + Q_p$$

$$Q_{td}C_{td} = Q_mC_m + Q_pC_p$$

The use of the above conservation of mass equations assumes there are no other major sources or sinks of chloride or water

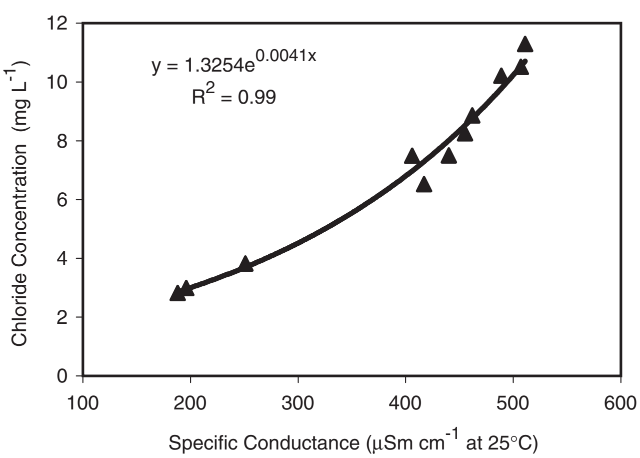

Fig. 2. Chloride concentration and specific conductance in tile drain effluent for the May 2004 storms at the Leary Weber Ditch tile drain study site. Regression equation subsequently used to estimate chloride concentrations of tile drain effluent in 15-min intervals through the storm hydrographs.

to the tile drain. The terms Q_{td}, Q_m, and Q_p represent the tile drain, matrix, and preferential flows, respectively. The terms C_{td}, C_m, and C_p represent the chloride concentrations in the tile drain effluent, matrix flow, and preferential flow, respectively. The values of Q_{td} were measured. The value used for C_m was the average of the chloride concentrations measured in the tile drain effluent during periods of baseflow, where C_p was the average of the chloride concentrations measured in overland flow water during the two May 2004 storms. The C_{td} values were interpolated based on the relation shown in Fig. 2. The computed values for the preferential flow and matrix flow then were plotted against time to produce the separated storm hydrographs.

A source of uncertainty in the mixing analysis is the estimate of chloride concentration from specific conductance. Uncertainty from the regression model used to predict chloride concentration from specific conductance may be small ($R^2 = 0.99$); however, this relation is based on a limited amount of data (Fig. 2).

Another source of uncertainty in the mixing analysis is the use of average chloride concentrations from the overland flow and tile drain low flow samples to represent preferential and matrix flow concentrations. This uncertainty was evaluated by a comparison of the mixing analysis (average concentrations) to a mixing analysis that used measured maximum and minimum concentrations, for these sites. Specifically, the maximum measured chloride concentration in the overland flow samples and the minimum measured chloride concentration in the tile drain baseflow samples were used in the second mixing analysis to minimize the difference between the two sources. The average difference between the two mixing analyses for the percent contribution of preferential flow and matrix water throughout the two May 2004 storms was 6.7% with a range from 0.0 to 22% Therefore, uncertainties based on the values selected to represent preferential and matrix flow appear to be small.

RESULTS AND DISCUSSION

The discussion is based on each of three individual storm hydrographs: 19 May, 30 May, and November 2004. Figure 3 shows the rainfall and tile drain flow from 2 Apr. 2004 through 3 Dec. 2004. Water samples collected during the November 2004 storm were not analyzed for glyphosate.

Figures 4 and 5 show the result of the hydrograph separation, based on the simple mixing analysis for the May 2004 storms. These two storms vary greatly in total

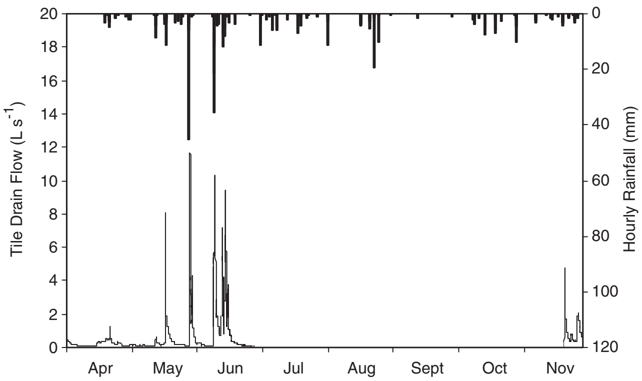

Fig. 3. April through December 2004 hourly rainfall and tile drain flow.

rainfall and intensity, and subsequently the hydrographs also vary. Five days before the May 19 storm, approximately 14.7 mm of rain fell during a 4-h period, producing a small rise in tile drain flow, with a peak of 0.6 L s^{-1}. This rainfall minimally affected the water table levels. During the 3 h before the 19 May storm, approximately 7.9 mm of rain fell. Between 01:00 and 02:00 on May 19, approximately 11.4 mm of rain fell. The tile drain hydrograph showed an increase in flow at 01:30 (Fig. 4C) on the same date, and the soil water piezometer showed an increase in water level between 01:30 and 01:45. The tile drain flow peaked at 8.1 L s^{-1}. Approximately 11% of the total storm flow came from preferential flow. This contribution falls within the range estimated by Kumar et al. (1997) of between 10 and 20% for most storms over time. Of interest was the quick response of the tile drain flow to the rainfall within the same hour of peak rainfall. In addition, tile drain effluent contained appreciable amounts of water from preferential flow at the onset of the increased tile drain flow (Fig. 4C); the largest percentage of preferential flow (40%) was just before and at the peak of the tile drain flow. The contribution of preferential flow also was seen during the recession of the hydrograph. The discharge-based hydrograph separation techniques used in Kumar et al. (1997) did not include preferential flow contributions during the recession. Kumar et al. (1997) note that these contributions are likely but small, compared to the overall contributions. The chloride-based hydrograph separation of the 19 May storm agrees with the suggestions in Kumar et al. (1997).

In contrast, the 30 May storm was of larger intensity and a shorter duration than the 19 May storm (Fig. 5). During the week preceding this storm, approximately 15.5 mm of rainfall were recorded; none of this rainfall was greater than 3.8 mm h^{-1} in intensity, and it did not increase tile drain flow. The water table level rose gradually during the week before the 30 May storm. Between 19:00 and 21:00, approximately 7.6 mm of rain fell; there was no tile drain hydrograph response. Between 21:00 and 22:00, approximately 45.2 mm of rain fell, and tile drain flow began to rise at 21:15 (Fig. 5C). Flow from the tile drain peaked (11.7 L s^{-1}) at 23:45 on 30 May. Preferential flow contributed approximately 51% of the total storm flow and 81% at the peak of the hydrograph. This contribution was higher than the typical contribution expected by Kumar et al. (1997). Kumar et al. (1997) also found, however, that high-intensity storms contribute larger proportions of preferential flow to the tile drains than lower intensity storms. Like the 19 May storm, the contribution of preferential flow to the tile drain was seen at the onset of the increased tile drain flow (Fig. 5C) and continued, to a lesser extent, during the recession.

Along with preferential flow, another mechanism that may affect tile drain response to rainfall is the proximity of the water table capillary fringe to land surface. Water table levels rose in response to the rainfall for both storms but at a much slower rate for the 19 May storm. This difference in the rates of water level increases reflects the difference in intensity and magnitude of rainfall during these two storms. The water table during the 30 May storm rose quickly, within 12 h to near land surface, causing saturated conditions in some areas and localized flooding. The rise in the water table and the subsequent loss of the unsaturated zone indicates that some of the flow identified as preferential flow in Fig. 5 more likely represents water moving to the tile drain by the steep gradient of the water table near the tile. Gillham (1984) found that in areas where the capillary fringe extended to the land surface, the addition of small amounts of rainfall raised the water table disproportionately higher than expected. In essence, the new shallow water table would be in the area that previously was occupied by the capillary fringe at or near land surface. In fine-textured soils, the capillary fringe may extend several meters upward from the water table. If the capillary fringe extended to the land surface, small amounts of rainfall would result in large increases in tile drain flow because of the saturation and the hydraulic connectivity of the system. The resulting steep gradients of the water table near the tile drain would transport water and solutes quickly to the tile.

Gillham (1984) described the capillary fringe effect as rapid with water table increases resulting within minutes of the addition of water to the land surface. The 30 May storm showed the quicker and higher rise in the water-table level of the two storms, but the rate of rise does not appear as rapid as that described in Gillham (1984). The piezometer was in a different field than the tile drain and the actual changes in the water table near the tile drain were not measured. Because of the lack of water table-level data near and at the tile drain, it may not be possible to make clear distinctions between preferential flow and capillary fringe mechanisms in water and solute transport during the hydrograph. Inclusion of shallow piezometers near the tile drain may help future studies better interpret the effects of the dynamic water table on water and solute transport.

Comparisons of estimated preferential flow to measured glyphosate concentrations suggest that preferential flow is an important transport mechanism for that pesticide. Figures 4 and 5 show the glyphosate levels for samples collected during the two May storms. Glyphosate, a common herbicide, has a high K_{oc} (organic carbon adsorption coefficient), which infers that it is more likely to adsorb to soil particles and less likely to leach

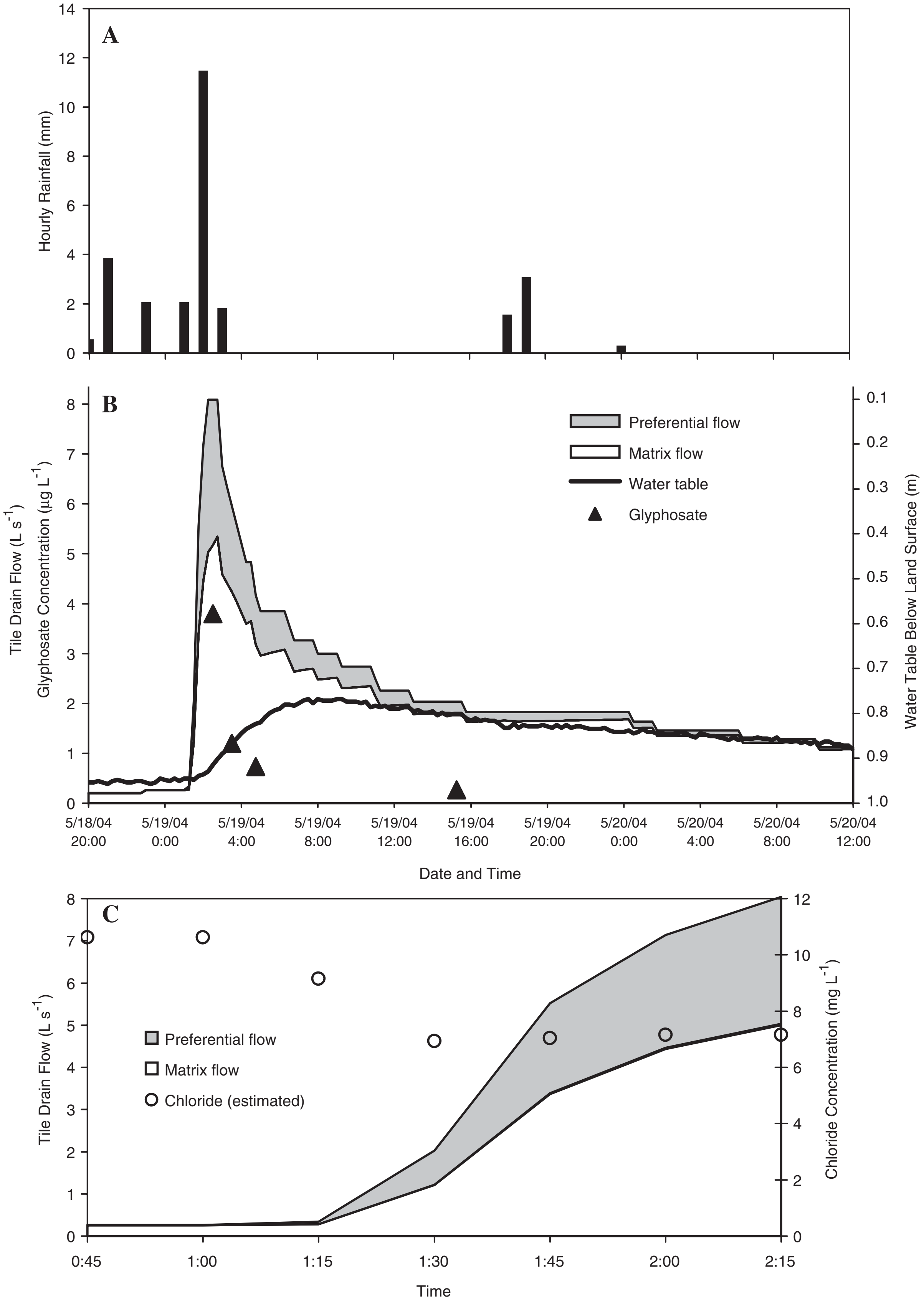

Fig. 4. (A) Hourly rainfall for the 19 May storm; (B) separated tile drain flow hydrograph, water table levels, and glyphosate concentrations for the storm; (C) closer look at the separated tile drain flow hydrograph at the time of increased flow. Tile drain flow hydrograph is separated into preferential and matrix flows by use of a simple chloride mixing analysis.

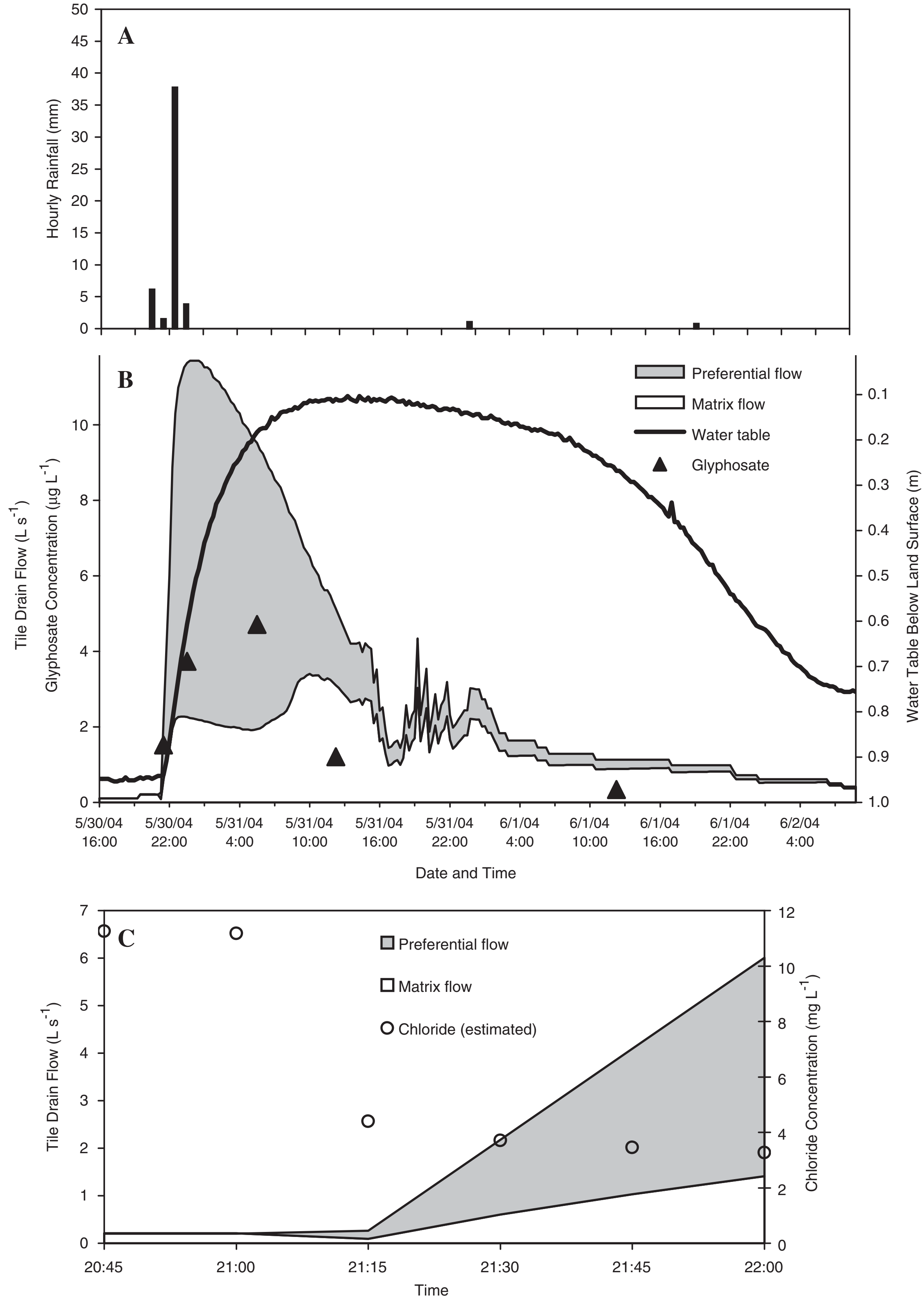

Fig. 5. (A) Hourly rainfall for the 30 May storm; (B) separated tile drain flow hydrograph, water table levels, and glyphosate concentrations for the storm; (C) closer look at the separated tile drain flow hydrograph at the time of increased flow. Tile drain flow hydrograph is separated into preferential and matrix flows by use of a simple chloride mixing analysis.

through soils with water movement than a chemical with a low K_{oc}. Glyphosate was applied 2 d before the 19 May storm. Water samples for glyphosate analysis were not collected during the rising part of the 19 May storm because of equipment failure. The first water sample coincided with the peak of tile drain flow and had a glyphosate concentration of 3.8 μg L^{-1}. However, the peak glyphosate concentration in the tile drain effluent may have occurred before the peak tile drain flow and may have higher than the measured 3.8 μg L^{-1}. Subsequent water samples after the peak tile drain flow showed the glyphosate concentrations to be decreasing with the recession of the tile drain flow; final sample concentration was 0.15 μg L^{-1}. Traditional advection-dispersion models likely would not be able to account for the quick glyphosate appearance in tile drain effluent during the 19 May storm. Preferential flow, as seen in the hydrograph separation, however, may be the transport mechanism that delivered glyphosate to the tile drain (Steenhuis et al., 1997; Kladivko et al., 2001). The highest glyphosate concentrations coincided with the highest proportion of preferential flow contributions.

Likewise, the glyphosate concentrations seen with the 30 May storm follow the preferential flow contributions (Fig. 5). The first water sample from this storm coincided with the rising part of the storm hydrograph and had a glyphosate concentration of 1.5 μg L^{-1}. The glyphosate concentration in water samples peaked (4.7 μg L^{-1}) after the tile drain flow had peaked. Subsequent water samples showed the glyphosate concentrations to be decreasing in conjunction with the recession of the tile drain flow; the final sample concentration was 0.34 μg L^{-1}. Examination of Fig. 5 shows that the tile drain effluent glyphosate concentration may have peaked between the time the samples were collected on 30 May at 23:30 and 31 May at 05:30, during the highest contribution of preferential flow. Since only one sample was analyzed during the peak tile drain flow, the peak glyphosate concentration in the tile drain effluent was missed. As noted by Kung et al. (2000) and other researchers, understanding the preferential flow characteristics of a tile drain is critical to planning when tile drain sampling should occur over the course of the storm hydrograph.

Both of the May 2004 storms after glyphosate application illustrate the significance of the preferential flow in pesticide transport. Glyphosate, a pesticide with high K_{oc}, would be expected to move poorly through the soil. Vereecken (2005) reviewed numerous glyphosate transport studies and found that the K_{oc} value is not a good indicator for the transport of glyphosate through soils, and that preferential flow is a major factor in glyphosate transport to tile drains. Preferential flow bypasses the soil matrix and delivers glyphosate to the tile drain and shallow ground water. Kjaer et al. (2005) found that glyphosate leached to tile drains in loamy soil with pronounced macropore flow, in contrast to minimal glyphosate leaching in sandy soils that lack macropores. In the May 2004 storms, a strong positive relation was seen between the estimated amount of preferential flow and glyphosate concentrations (Fig. 6). However, this positive relation appears to flatten at higher levels of preferential flow.

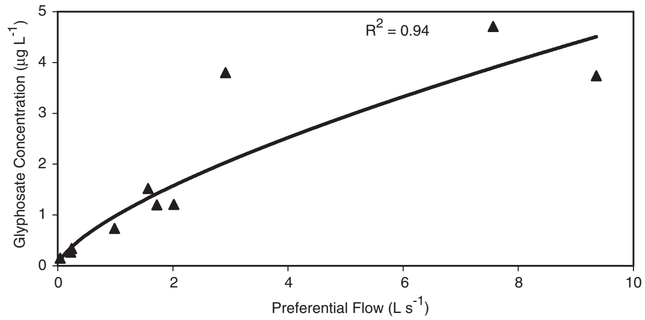

Fig. 6. Glyphosate concentration and preferential flow in the tile drain during the May 2004 storms at the Leary Weber Ditch tile drain study site.

Kladivko et al. (1991) found that pesticide transport to tile drains was storm driven and that storms following the initial storm after pesticide application produced lower concentrations of pesticides in the tile-drain effluent than the initial storm. Essentially, the available pesticide pools decrease in surface soils over time through leaching, plant uptake, and degradation. Because glyphosate was applied before the 19 May storm and there was no application between the storms, the available glyphosate pool in the surface soils would be lower before the 30 May storm. Therefore, the peak glyphosate concentration during the 30 May storm would be expected to be lower than the peak of the 19 May storm. Comparison of the maximum measured glyphosate concentrations between the 19 May and 30 May storms, however, implies the glyphosate concentrations between these two storms were similar and possibly, the second storm may have had a higher glyphosate concentration, 3.8 and 4.7 μg L^{-1}, respectively. It is likely that the peak glyphosate concentrations in tile drain effluent were missed in the timing of sample collection for both storms. In addition, comparison of the maximum measured glyphosate concentrations does not account for the differences in preferential flow contributions between the two storms. Figure 7 shows the relation between glyphosate concentrations and preferential flow as a percentage of total tile drain flow. The slope of this relation for the 19 May storm is steeper than that of the 30 May storm,

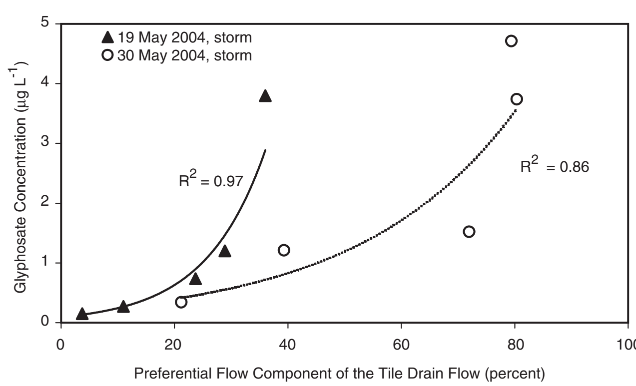

Fig. 7. Glyphosate concentration and preferential flow as a percentage of total tile drain flow during the May 2004 storms at the Leary Weber Ditch tile drain study site.

indicating that the 19 May storm had higher glyphosate concentrations related to lower percentages of preferential flow in the tile drain effluent as compared to the 30 May storm. As the glyphosate pool in the surface soils decrease through leaching, plant uptake, and degradation, greater amounts of preferential flow, as a percentage of tile drain effluent, were required to reach the concentration levels found with the 19 May storm that immediately followed application. If no additional glyphosate was applied to the field, the relations for the two storms in Fig. 7 suggest, that for subsequent storms, the relation between glyphosate concentrations and preferential flow as a percentage of tile drain effluent would progressively flatten due to the decreasing pool of available glyphosate in the surface soils.

Both of these storms occurred within 2 wk of glyphosate application; therefore, glyphosate was available on the soil surface for transport. Low concentrations of glyphosate in the tile drain effluent were measured; to illustrate, the maximum tile drain effluent concentration was 4.71 $\mu g\ L^{-1}$ and the maximum overland flow concentration was 427 $\mu g\ L^{-1}$. These concentrations show that although transport occurred, the glyphosate concentrations delivered in the tile drains are small compared to overland flow as was also found by Kladivko et al. (2001).

The tile drain was not flowing from July 2004 through 24 November 2004, and during this period water levels recorded at the piezometer reached the lowest points during the entire 2004 record. During the week preceding the November 2004 storm, approximately 24.9 mm of rainfall were recorded; none of this rainfall, however, was greater than 3.3 mm h^{-1} in intensity. It is probable that this rainfall did not initiate tile drain flow because the water table was low as a result of the extended dry period. At the beginning of November 2004, the water level recorded at the piezometer began to steadily rise. The tile drain began flowing on 24 November at 12:45 (Fig. 8). Unlike the May storms, the tile drain flow increase was not associated with a period of intense rainfall. Approximately 11.4 mm of rain fell in the 3 h before the initiation of tile flow. The first peak flow from the tile drain, 4.7 L s^{-1}, was at 17:00 on 24 November, followed by subsequent peaks corresponding to additional rainfall. Following the extended dry period of summer and fall, this November 2004 storm was characterized by repeated low-intensity rains with subsequent and immediate responses in the tile drain flow (Fig. 8).

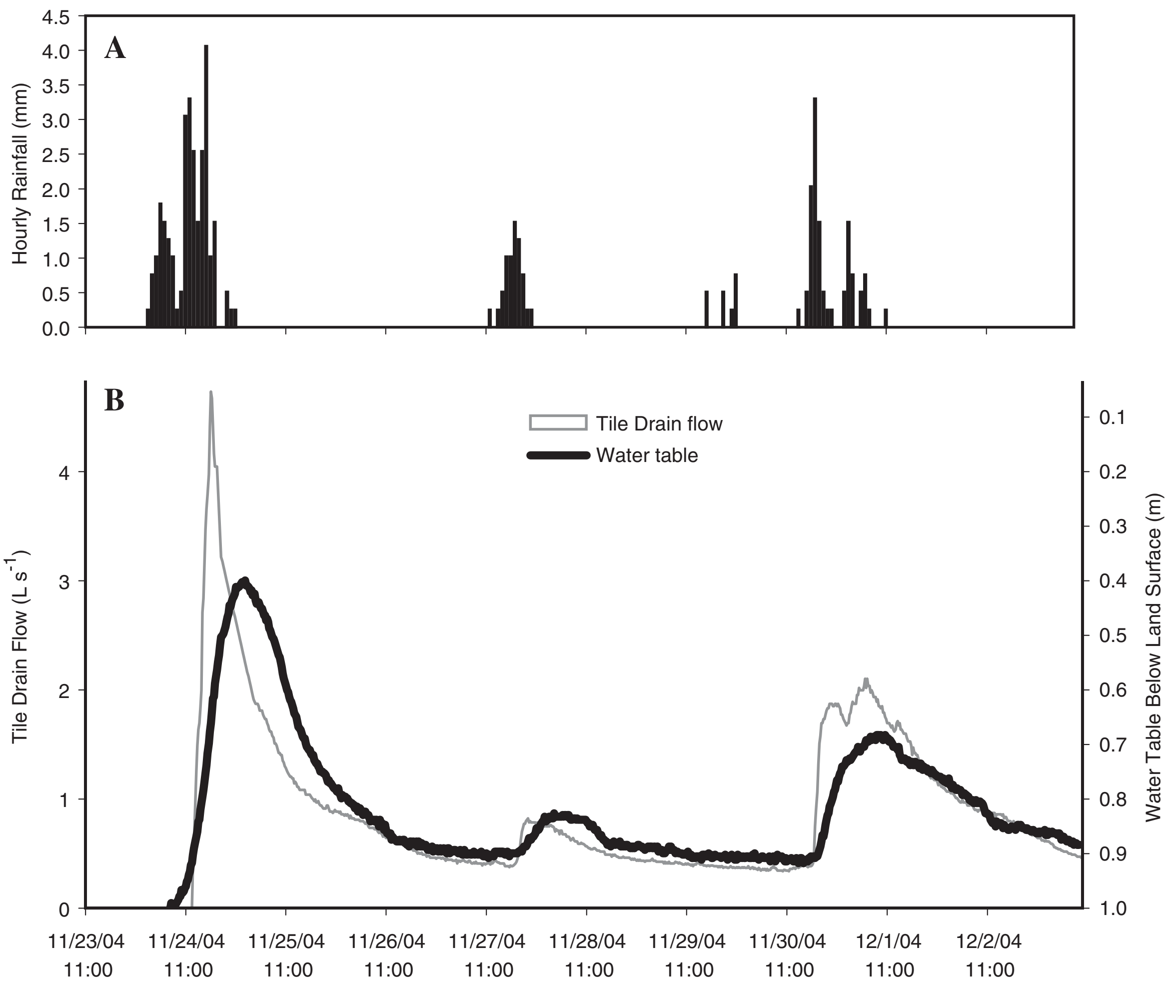

Fig. 8. (A) Hourly rainfall for the November 2004 storm and (B) tile drain flow hydrograph and water table levels at the Leary Weber Ditch tile drain study site.

Unlike the May 2004 storms, the November 2004 storm did not show the same relations between specific conductance, tile drain flow, and chloride (Table 1). The relation between tile drain flow and chloride concentrations reversed from a strong negative correlation during the May 2004 storms to a strong positive correlation during the November 2004 storm. The application of muriate of potash to the tile drain field during late fall 2004 presumably changed the field surface water (preferential flow) concentrations of chloride. Chloride concentrations measured in the tile drain effluent for this storm were two to three times higher than concentrations measured in the May 2004 storms. Chloride concentration data for the field surface water (overland flow) were not available for this storm; therefore, it was not possible to do the chloride simple mixing analysis. Other anions, such as sulfate, were considered in substitution for chloride in the simple mixing analysis (Table 1). The relations between the anions, flow, and specific conductance, however, were not strong enough to estimate concentrations throughout the hydrograph.

The application of muriate of potash to the tile drain field was one of several factors that distinguish the November 2004 storm from the May 2004 storms. The tile drain had not been flowing for approximately 4 mo before the November 2004 storm; the tile drain had been flowing before the May 2004 storms. The lowest water table levels were seen during the 4 mo before the November 2004 storm. In addition, unlike the May 2004 storms, no high-intensity rainfall was associated with the onset of tile drain flow. During dry antecedent conditions, preferential flow pathways may behave like dead-end pores, and water and solutes moving with preferential flow may be pulled into drier parts of the deeper soil profile (Gish et al., 2004). This would make distinguishing preferential from matrix flow (with nonapplied tracers) difficult because of the mixing of the two waters in the saturated areas. Finally, the field surface had been chisel-plowed before the November 2004 storm, obliterating surface fissures. In contrast, shrink–swell fissures were visible before the May 2004 storms. Thomas and Phillips (1979), however, suggest that macropores need not extend to the field surface and that the increase in hydraulic conductivity caused by the cultivation of the soils will move water down to where macropores still may exist. If preferential flow pathways were active during the early part of the November 2004 storm, the majority of the water would have gone to elevating the water table. The tile drain did not flow until the water table was high enough to inundate the tile drain. Therefore, the water table would more reflect the preferential flow contributions, and separation of the components during the storm would not be possible.

CONCLUSIONS

The collection of major ion and specific conductance data, in conjunction with tile drain flow data, allows for estimation of preferential flow contributions to the tile drain through simple mixing analysis of existing solutes and hydrograph separation. This analysis for the two May 2004 storms indicates that preferential flow to tile drains can occur at the onset of increased flow and peak in conjunction with the total peak flow. In addition, preferential flow contributions, although small, also are seen along the recession of the hydrograph. The 30 May storm shows that large-intensity storms can produce large contributions of preferential flow.

Preferential flow contributions were 11 and 51% of the total tile drain flow for the two storm hydrographs and were 40 and 81% of peak flows. Similar monitoring and evaluation of tile drain flow over several years may provide insight into better quantifying preferential flow contributions and understanding the conditions favoring preferential flow. If applicable in a particular environmental setting, the technique of using existing ions as chemical tracers for preferential flow offers an alternative to traditional tracer studies.

Along with preferential flow, the dynamic water table influences the transport of water and solutes to the tile drain. Mechanisms such as the capillary fringe effect can be investigated more fully in environmental settings where they may be a factor. Inclusion of shallow piezometers near the tile drain and collection of water-level data on an hourly or more frequent basis during storms may help the understanding of these effects.

The transport of glyphosate appears to be driven primarily by preferential flow for these two storms. The concentrations of glyphosate in tile drain effluent were the highest when the proportion of preferential flow contribution was the highest. This finding is critical in understanding when tile drain sampling should occur over the course of the storm hydrograph to characterize glyphosate transport through preferential flow. For example, the glyphosate concentration during the 30 May storm likely peaked between the times the two samples were collected for analysis. Knowledge of the preferential flow characteristics of this tile drain and the relation to glyphosate concentrations could have helped in the selection of which samples to analyze when targeting peak glyphosate concentrations in the tile drain flow.

The strong positive relations between glyphosate concentrations and contributions from preferential flow from the two storms on an operational farm field confirm the past efforts in modeling that were based on experimental field plots. Similar hydrograph-separation techniques and pesticide data collection over several years under various antecedent conditions could benefit the understanding of solute transport and preferential flow.

The November 2004 storm illustrates a potential downfall of using major ion chemistry data without applied tracers for hydrograph separation from tile drains. Recent chemical application to the fields changed the tracer concentration in at least one of the sources and created a condition where the tracer source concentration was not stable.

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REFERENCES

American Public Health Association. 1998. Standard methods for the examination of water and wastewater. 20th ed. APHA, AWWA, and WEF. Washington, DC.

Brouder, S., B. Hofmann, E. Kladivko, R. Turco, A. Bongen, and J. Frankenberger. 2005. Interpreting nitrate concentration in tile drainage water. Purdue University Extension Agronomy Guide. AY-318-W.

Burns, D.A., J.J. McDonnell, R.P. Hooper, N.E. Peters, J.E. Freer, C. Kendall, and K. Beven. 2001. Quantifying contributions to storm runoff through end-member mixing analysis and hydrologic measurements at the Panola Mountain Research Watershed (Georgia, USA). Hydrol. Processes 15:1903–1924.

David, M.B., L.E. Gentry, D.A. Kovacic, and K.M. Smith. 1997. Nitrogen balance in and export from an agricultural watershed. J. Environ. Qual. 26:1038–1048.

Fenelon, J.M., and R.C. Moore. 1998. Transport of agrichemicals to ground and surface water in a small Central Indiana watershed. J. Environ. Qual. 27:884–894.

Fishman, M.J. (ed.). 1993. Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory: Determination of inorganic and organic constituents in water and fluvial sediments. USGS Rep. 93-125. U.S. Gov. Print. Office, Washington, D.C.

Fishman, M.J., and L.C. Friedman. (ed.) 1989. Methods for determination of inorganic substances in water and fluvial sediments. USGS Techniques of Water-Resources Investigations. 3rd ed. U.S. Gov. Print. Office, Washington, D.C.

Gentry, L.E., M.B. David, K.M. Smith, and D.A. Kovacic. 1998. Nitrogen cycling and tile drainage nitrate loss in a corn/soybean watershed. Agric. Ecosyst. Environ. 68:85–97.

Gentry, L.E., M.B. David, K.M. Smith–Starks, and D.A. Kovacic. 2000. Nitrogen fertilizer and herbicide transport from tile drained fields. J. Environ. Qual. 29:232–240.

Gillham, R.W. 1984. The capillary fringe and its effect on water-table response. J. Hydrol. 67:307–324.

Gish, T.J., K.-J.S. Kung, D.C. Perry, J. Posner, G. Bubenzer, C.S. Helling, E.J. Kladivko, and T.S. Steenhuis. 2004. Vadose zone processes and chemical transport: Impact of preferential flow at varying irrigation rates by quantifying mass fluxes. J. Environ. Qual. 33: 1033–1040.

Hager, W.H. 1988. Mobile flume for circular channel. J. Irrig. Drain. Eng. 114(3):520–534.

Hyer, K.E., G.M. Hornberger, and J.S. Herman. 2001. Processes controlling the episodic streamwater transport of atrazine and other agrichemicals in an agricultural watershed. J. Hydrol. 254:47–66.

Kjaer, J., P. Olsen, M. Ullum, and R. Grant. 2005. Leaching of glyphosate and amino-methylphosphonic acid from Danish agricultural field sites. J. Environ. Qual. 34:608–620.

Kladivko, E.J., L.C. Brown, and J.L. Baker. 2001. Pesticide transport to subsurface tile drains in humid regions of North America. Crit. Rev. Environ. Sci. Technol. 31(1):1–62.

Kladivko, E.J., J.R. Frankenberger, D.B. Jaynes, D.W. Meek, B.J. Jenkinson, and N.R. Fausey. 2004. Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system. J. Environ. Qual. 33:1803–1813.

Kladivko, E.J., J. Grochulska, R.F. Turco, G.E. Van Scoyoc, and J.D. Eigel. 1999. Pesticide and nitrate transport into subsurface tile drains of different spacings. J. Environ. Qual. 28:997–1004.

Kladivko, E.J., G.E. Van Scoyoc, E.J. Monke, K.M. Oates, and W. Pask. 1991. Pesticide and nutrient movement into subsurface tile drains on a silt loam soil in Indiana. J. Environ. Qual. 20:264–270.

Kumar, A., R.S. Kanwar, and G.R. Hallberg. 1997. Separating preferential and matrix flows using subsurface tile flow data. J. Environ. Sci. Health, Part A: Environ. Sci. Eng. Toxic Hazard. Subst. Control. 32(6):1711–1729.

Kung, K.-J.S., E.J. Kladivko, T.J. Gish, T.S. Steenhuis, G. Bubenzer, and C.S. Helling. 2000. Quantifying preferential flow by breakthrough of sequentially applied tracers: Silt loam soil. Soil Sci. Soc. Am. J. 64:1296–1304.

Lapham, W.W., F.D. Wilde, and M.T. Koterba. 1996. Guidelines and standard procedures for studies of groundwater quality: Selection and installation of wells, and supporting documentation. USGS Water Resources Investigations Rep. 96-4233. U.S.Gov. Print. Office, Washington, D.C.

Lee, E.A., A.P. Strahan, and E.M. Thurman. 2002. Methods of analysis by the U.S. Geological Survey Organic Geochemistry Research Group: Determination of glyphosate, aminomethylphosphonic acid, and glufosinate in water using solid-phase extraction and high-performance liquid chromatography/mass spectrometry. USGS Rep. 01-454. U.S. Gov. Print. Office, Washington, D.C.

Richard, T.L., and T.S. Steenhuis. 1988. Tile drain sampling of preferential flow on a field scale. J. Contam. Hydrol. 3:307–325.

Samani, Z., and E. Herrera. 1996. A low-cost water measuring device. Guide M-226:PH-4–205 New Mexico State University Cooperative Extension Service, Las Cruces, NM.

Samani, Z., S. Jorat, and M. Yousaf. 1991. Hydraulic characteristics of circular flume. J. Irrig. Drain. Eng. 1117(4):558–566.

Samani, Z., and H. Magallanez. 2000. Simple flume for flow measurement in open channel. J. Irrig. Drain. Eng. 126(2):127–129.

Soenksen, P.J. 1996. Transport of agricultural chemicals in surface flow, tileflow, and streamflow of Walnut Creek Watershed near Ames, Iowa, April 1991–September 1993. USGS Water-Resources Investigations Rep. 96-4017. U.S. Gov. Print. Office, Washington, D.C.

Steenhuis, T.S., M. Bodnar, L.D. Geohring, S.-A.E. Aburime, and R. Wallach. 1997. A simple model for predicting solute concentration in agricultural tile lines shortly after application. Hydrol. Earth Syst. Sci. 4:823–833.

Steenhuis, T.S., J. Boll, G. Shalit, J.S. Selker, and I.A. Merwin. 1994. A simple equation for predicting preferential flow solute concentrations. J. Environ. Qual. 23:1058–1064.

Thomas, G.W., and R.E. Phillips. 1979. Consequences of water movement in macropores. J. Environ. Qual. 8:149–152.

USDA. 1978. Soil Survey of Hancock County, Indiana. USDA, Washington, D.C.

USDA. 1987. Farm drainage in the United States: History, status, and prospects. USDA-ERS. Misc. Pub. No. 1455. USDA, Washington, D.C.

USGS. 2006. National field manual for the collection of water-quality data. U.S. Geological Survey Techniques of Water-Resources Investigations. book 9. A1–A9. (Available online with updates at http://pubs.water.usgs.gov/twri9A.) (accessed 1 Oct. 2005; verified 6 June 2006).

Vereecken, H. 2005. Mobility and leaching of glyphosate: A review. Pest Manag. Sci. 61:1139–1151.

White, R.E. 1985. The influence of macropores on the transport of dissolved and suspended matter through soil. Adv. Soil Sci. 3:95–120.